Micromachined Ultrasonic Transducers

Annual Summary Report

June 1, 1996 to May 31, 1997

Grant N00014-94-1-0730

G. L. Report No. 5517

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June 1997

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)

2. REPORT DATE
June 1997

3. REPORT TYPE AND DATES COVERED
Summary 6-1-96 to 5-31-97

4. TITLE AND SUBTITLE
MICROMACHINED ULTRASONIC TRANSDUCERS

5. FUNDING NUMBERS
N00014-94-1-0730
16G374

6. AUTHOR(S)
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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
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8. PERFORMING ORGANIZATION REPORT NUMBER
G.L. 5517

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Logan E. Hargrove (Code 312)
Office of Naval Research
Ballston Tower One
800 North Quincy Street
Arlington, Virginia 22217-5660

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES
The views, opinions and/or findings contained in this report are those of the authors and should not be construed as an official Department of Defense position, policy or decision unless otherwise documented.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release;
distribution unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)
Microfabricated ultrasonic transducers have been generated which operate in both liquids and gases. Air coupled through transmission of aluminum was observed for the first time using a pair of 2.3 MHz transducers. The dynamic range of the transducers was 110 dB, and the received signal had an SNR of 30 dB. Air coupled through transmission of steel and glass has also been observed. A theoretical model for the transducers has been refined and agrees well with experimental results. A robust microfabrication process has been developed and was used to generate air transducers which resonate from 2 to 12 MHz, as well as immersion transducers that operate in water from 1 to 20 MHz with a 60 dB dynamic range. Optimized immersion and air transducers have been designed and a dynamic range above 110 dB is anticipated. This development effort finds applications in hydrophones, medical ultrasound, nondestructive evaluation, ranging, flow metering, and scanning tip force sensing and lithography.

14. SUBJECT TERMS
Ultrasound, Micromachines, Transducer, Capacitive
Immersion, Airborne, Physical Acoustics

15. NUMBER OF PAGES
5

16. PRICE CODE
NTIS only

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	SAR

ANNUAL SUMMARY REPORT
JUNE 1, 1996 TO MAY 31, 1997

A. Description of Project

The objective of the Micromachined Ultrasonic Transducer (MUT) development effort is to generate practical fabrication procedures and robust theoretical models of novel ultrasonic sensors and actuators. These transducers should constitute a superior alternative to conventional piezoelectric devices in many applications. Although each unique application will most likely require its own optimized version of a MUT, the general principles and design rules elucidated by the development effort should impact the areas of hydrophonics, nondestructive evaluation, medical imaging, ranging, flow metering, and even scanning tip imaging and lithography.

B. Approaches Taken

MUT development begins in the broadest sense with the definition of a thought paradigm. The formalism of electrical circuit networks is found to be most beneficial in designing transducers and transducer systems. In general terms, a transducer converts some form of energy (acoustic, chemical, optical, kinetic, etc.) into an electrical signal and vice versa. Thus, if equivalent circuits can be obtained which adequately represent the energy conversion process then the familiar concepts of ABCD matrices, two-port models, impedance matching, thermal noise sources, etc. can be applied to the design and analysis of a transducer system.

The approach towards MUT development is therefore to first develop an equivalent circuit for the energy conversion process. The more sophisticated the equivalent circuit, the more parameters it takes into account, such as the geometry of the transducer, the mechanical properties of its constituents, and parasitic losses, among others. Often, a computer simulation of the equivalent circuit behavior is necessary. When the transducer design is validated by preliminary calculations, process development is undertaken. Process development is a crucial part of the transducer development effort and can be time consuming due to its empirical nature. The microfabrication process is the enabling technology which delimits the design parameters of the transducers, so significant effort is placed in the refinement of the process. When process development results in viable devices, test beds are generated, including supporting electronics, in order to compare the true performance of the devices to theory. If necessary, optical tools can be used to measure the displacement at the transducer surface directly. Then, the device design, the theory, and the process are revised so that the subsequent generation of transducers is improved.

C. Accomplishments

Standard micromachining techniques have been used in unique combinations to fabricate transducers with resonant frequencies in the 2 to 12 MHz range in air. Transmission experiments have been performed repeatedly in air, with the most significant result being the air coupled transmission of 2.3 MHz ultrasound through aluminum, steel, and glass. The transducers used in the through transmission experiments have a dynamic range of 110 dB. One of the tricks employed to increase the dynamic range is the patterning of the electrode, so that inactive capacitance is minimized. In order to further increase the dynamic range, parasitic losses should be minimized.

Both the theory and the fabrication process have been modified for the development of immersion transducers. Initial unoptimized transducers were able to transmit from 1 to 20 MHz in water with a 60 dB dynamic range. The theoretical model predicts a transmission dynamic range as high as 140 dB in water when electronic noise is taken to be dominant. The fundamental thermal noise of the membrane in water is indeed lower than that of the electronics. It is anticipated that transducers with 120 dB of dynamic range and a 50% bandwidth can be realized.

A new fabrication process has been developed to generate arbitrarily shaped vacuum sealed elements. The ability to generate larger elements is anticipated to lead to the development of air transducers in the 100 Khz to 1 MHz range, as well as optimized immersion transducers. The fabrication process consists of a unique combination of standard micromachining techniques and is the subject of a current patent disclosure. This fabrication process yields matched transducers repeatably, including the pairs used for air coupled through transmission experiments. The new fabrication process constitutes a significant improvement over the process developed last year.

The equivalent circuit model for the transducers was refined to include the effects of membrane thickness. The effect of electrostatic spring softening has also been observed experimentally and explained theoretically. It has also been found through a series of vacuum experiments using unsealed transducers that the air in the transducer cavity has stiffening and dissipative effects, and a model accounting for them is currently being developed. Finally, membrane collapse, or knocking mode operation, has been observed experimentally for the first time.

The accomplishments achieved in this reporting period pave the way for many interesting investigations in the coming year. Most of our effort will be dedicated to the further refinement of theoretical understanding and to the design of experiments using the new transducers. Theoretical concerns include the secondary loss mechanisms of the transducer, from viscous damping to thermal transfer to leakage into the supporting structure. Experiments envisioned include the generation of images of defects in aluminum and composites by scanning air coupled transducers, transmission in water using optimized transducers, and various proof of principle experiments demonstrating the applicability of the transducers to ranging and flow metering. If time and resources permit, the non-

linear behavior of both the transducer and air, when displacements reach large-signal levels, will be investigated. The development effort has significant implications in the areas of medical ultrasound, underwater detection, non-destructive evaluation (manufacturing, materials characterization, and infrastructure inspections), flow metering, and position sensing.

OFFICE OF NAVAL RESEARCH
PUBLICATION/PATENTS/PRESENTATION/HONORS REPORT
for
01 June 96 through 31 May 97

Contract/Grant Number: N00014-94-1-0730

Contract/Grant Title: Micromachined Ultrasonic Transducers

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a. Number of Papers Submitted to Refereed Journals but not yet published: 1

b. Number of Papers Published in Refereed Journals: 1

c. Number of Books or Chapters Submitted but not yet Published: 0

d. Number of Books or Chapters Published: 0

e. Number of Printed Technical Report & Non-Refereed Papers: 1

f. Number of Patents Filed : 2+1 (in prep.)

g. Number of Patents Granted: 1

h. Number of Invited Presentations at Workshops or Prof. Society Meetings: 0

I. Number of Presentations at Workshops or Prof. Society Meetings: 1

j. Honors/Awards/Prized for Contract/Grant Employees: 0

k. Number of graduate students supported at least 25% this year this contract/grant: 1

l. Number of post docs supported at least 25% this year this contract/grant: 0

Graduate student FEMALE:	0	Post doc FEMALE:	0
Graduate student MINORITY:	0	Post doc MINORITY:	0
Graduate student ASIAN E/N:	0	Post doc ASIAN E/N:	0

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Papers published in refereed journals:

1. H. T. Soh, I. Ladabaum, A. Atalar, C. F. Quate, B. T. Khuri-Yakub, "Silicon micromachined ultrasonic immersion transducers," Applied Physics Letters, vol. 69, pp. 3674-3676, December 1996.

Printed technical reports & non-refereed papers

1. I. Ladabaum, X. Jin, H. T. Soh, F. Pierre, A. Atalar, B. T. Khuri-Yakub, "Micromachined ultrasonic transducers: towards robust models and immersion devices," presented at IEEE Ultrasonics Symposium, San Antonio, Texas, November 3-6, 1996; in 1996 Ultrasonics Symposium Proceedings (Institute of Electrical and Electronics Engineers, Inc., New York, 1996), pp. 335-338.

Invited presentations at workshops or professional society meetings:

1. Gordon Conference on NDE, Kimball Union, New Hampshire, August 19-23, 1996.

Contributed presentations at workshops or professional society meetings:

1. DARPA/ONR Workshop on Medical Ultrasonic Imaging Technology Development for Combat Casualty Care, Lansdowne, Virginia, February 12-14, 1996.

Honors/awards/prizes for contract/grant employees, such as scientific society and faculty awards/offices:

None